

STRUCTURES AND METHODS FOR FABRICATING INTEGRATED HBT/FET'S AT COMPETITIVE COST

FIELD OF INVENTION

This invention is related in general to HBT/FET fabrication technologies and in particular to structures and methods for fabricating integrated InGaP/GaAs HBT/FET's on the same chip at a competitive cost.

BACKGROUND OF INVENTION

InGaP/GaAs HBT Technology is very attractive for use in many commercial applications for its excellent reliability and thermal stability. The first generation of InGaP-based power amplifiers for wireless handsets, wireless LAN, broadband gain blocks, and high-speed fiber optic products have been successfully developed and marketed. For future generations of these products, it is important to reduce the die size and cost as well as to provide additional functionality with improved circuit performance. The integration of bipolar (HBT) and field effect transistors (FET or HEMT) on the same chip offers a unique way to achieve these goals. While the combination of bipolar and field effect devices in an integrated circuit is well known in the silicon world (BiCMOS), there has been no viable way to realize this concept in GaAs-based technologies for large volume commercial applications.

Several methods of integrating AlGaAs/GaAs HBT with field effect devices have been discussed in the literature. In one approach described in Ho *et al.*, "A GaAs BiFET LSI technology", GaAs IC Sym. Tech. Dig., 1994, p.47, and D. Cheskis *et al.*, "Co-integration of GaAlAs/GaAs HBT's and GaAs FET's with a simple manufacturable process", IEDM Tech. Dig., 1992, p. 91, the HBT emitter cap layer is used as a FET channel. This approach had two major drawbacks. First, the emitter resistance of the HBT is high and second, the parasitic effect of the base layer degrades FET performance and limits its applications.

Another approach is to grow HBT and HEMT structures by selective MBE growth. (See Streit, *et al.*, "Monolithik HEMT-HBT integration by selective MBE", IEEE Trans. Electron Devices, vol. 42, 1995, p.618 and Streit, *et al.*, "35 GHz HEMT amplifiers fabricated using integration HEMT-HBT material grown by selective MBE", IEEE Microwave Guided Wave Lett., vol. 4, 1994,p.361.) The problem with this approach is the requirement of epi-growth interruption, wafer processing and epi re-growth. These steps render this approach un-manufacturable (i.e. high cost) with poor epi quality control.

It has also been shown that AlGaAs/GaAs HBT may be grown on top of the HEMT in a single growth run. (See K. Itakura, Y. Shimamoto, T. Ueda, S. Katsu, D. Ueda, "A GaAs Bi-FET technology for large scale integration", IEDM Tech. Dig., 1989, p. 389.) In this approach the FET is merged into the collector of the HBT through a single epitaxial growth.

Several attempts have been also made to integrate InGaP/GaAs HBT with MESFET and HEMT. (See J. H. Tsai, "Characteristics of InGaP/GaAs co-integrated d-doped heterojunction bipolar transistor and doped-channel field effect transistor," Solid State Electronics, vol. 46., 2002, p. 45 and Yang *et al.*, "Integration of GaInP/GaAs heterojunction bipolar transistors and high electron mobility transistors", IEEE Electron Device Lett., vol. 17, no, 7, July 1996, p. 363. In these approaches the channel of the field effect devices used an InGaP layer with low mobility and saturation velocity which results in high linear resistance and poor high frequency performance. These devices also show threshold voltages lower than -2 Volts. These characteristics, however, make them largely unsuitable for commercial applications.

There is therefore a need for methods and epitaxial structures for fabricating integrated pairs of GaAs-based HBT and FET devices that are suitable for commercial applications.

SUMMARY OF INVENTION

One aspect of the present invention is a structure comprising a first epitaxial layer on top of the substrate; a second layer structure on top of the first epitaxial layer, and a third epitaxial layer on top of the second epitaxial layer. In one embodiment, the first epitaxial layer forms a portion of a field effect transistor. The third epitaxial layer forms a portion of a bipolar transistor. The second epitaxial layer is shared by the bipolar and the field effect transistors.

Another aspect of the present invention comprises a method of fabricating integrated bipolar transistor and field effect transistors on the same substrate. In one embodiment, the method comprises the steps of: providing the three-layer structure comprising a first, second, and third epitaxial layer; fabricating the bipolar transistor from the first epitaxial layer of the structure; isolating the second and third epitaxial layers of the structure; and optimizing the field effect transistor and the bipolar transistor independently.

Yet another aspect of the present invention comprises an integrated pair of bipolar and field effect transistors. In one embodiment, the bipolar and field effect transistors share a contact layer. The contact layer serves as both the cap layer for the field effect transistor and the subcollector layer for the bipolar transistor.

Yet another aspect of the present invention comprises a method of fabricating an epitaxial structure for fabricating an integrated pair of GaAs-based HBT and FET. In one embodiment, the method comprises the steps of: growing a first set of epitaxial layers for fabricating the FET on a semi-insulating GaAs substrate; fabricating a highly doped thick GaAs layer serving as the cap layer for the FET and the subcollector layer for the HBT; and producing a second set of epitaxial layers for fabricating the HBT.

BRIEF DESCRIPTION OF DRAWINGS

Fig. 1 illustrates a structure for fabricating an integrated FET and HBT pair in one embodiment of this invention.

Figs. 2a-2b demonstrate the results of a sensitivity study of the relationships between subcollector thickness and the power-added efficiency (PAE), cut-off frequency (f_t) and maximum oscillating frequency (f_{max}) characteristics of the HBT.

Fig. 3 describes the characteristics of each layer in the epitaxial structure in one embodiment of this invention.

Fig. 4 shows the process flow used in the fabrication of HBT/FETs according to one embodiment of this invention.

Fig. 5 shows a cross-section view of the integrated pair of HBT and FET formed during the process of **Fig. 4**.

Figs. 6-7 summarize the characteristics of the HBT and MESFET fabricated according to one embodiment of this invention.

DETAILED DESCRIPTION OF PREFERRED EMBODIMENTS

Fig. 1 illustrates the formation of the structure for fabricating an integrated FET and HBT pair in one embodiment of this invention. Substrate **101** is first provided and may be a semi-insulating GaAs wafer substrate, or any suitable substrate for fabricating the integrated HBT and FET pair. The GaAs substrate **101** may be fabricated using well-known crystal-growth technologies such as the Czochralski technique or the Bridgman technique. Detailed descriptions of these techniques can be found, for example, at page 343-349 of S.M. Sze, “Semiconductor Devices: Physics and Technology”, 2nd Ed., John Wiley & Sons, Inc. 2002.

After providing the substrate **101**, a first epitaxial structure **102** may be grown on top of the substrate **101**. The epitaxial structure **102** may comprise one or more epitaxial layers. The epitaxial structure **102** (and other epitaxial structures grown on top of it) may be fabricated using well-known technologies such as chemical vapor deposition (CVD), Metalorganic CVD (MOCVD), or molecular beam epitaxy (MBE). Detailed descriptions of these technologies can be found, for example, at page 356-361 of S.M. Sze, “Semiconductor Devices: Physics and Technology”, 2nd Ed., John Wiley & Sons, Inc. 2002.

The composition and thickness of each epitaxial layer in the epitaxial structure **102** may depend on the application and the type of FET that is being fabricated. In **Fig. 1**, the epitaxial structure **102** comprises a first set of epitaxial layers **121** and a second set of epitaxial layers **122**. The first set of epitaxial layers **121** may be used to form a low leakage buffer layer, which can help reduce the substrate leak current and output conductance, thereby improving the efficiency of the FET. The low leakage buffer layer may (but not necessarily) further comprise one or more undoped GaAs or AlGaAs layers. The thickness of each layer and the aluminum mole fraction of each AlGaAs layer may be chosen to optimize the performance of the FET or the HBT. The low leakage buffer layer may comprise an undoped GaAs layer approximately 75 nm (1 nm = 10^{-9} meter) thick and an undoped AlGaAs layer with approximately 250 nm thick. The undoped AlGaAs may comprise approximately 25% Al.

The second set of epitaxial layers **122** may be used to form the epitaxial structure for the FET. The layer structure and the thickness of each epitaxial layer in the epitaxial layers **122** may depend on the application and the type of FET that is being fabricated. In **Fig. 1**, the epitaxial layers **122** form the epitaxial structure for a MESFET. The set of epitaxial layers **122** may comprise an approximately 50 nm thick undoped GaAs spacer layer and a doped GaAs channel layer of about 120 nm thick. The spacer layer can help carrier confinement and provide spatial separation between the active channel and the AlGaAs/GaAs heterojunction in the buffer layer **121**. The doping type and concentration of the channel layer depends on the application. For example, the channel layer may be doped with n-type Silicon with a doping concentration of approximately $3.2 \times 10^{17} \text{ cm}^{-3}$. Moreover, a thin (about 20 nm) highly doped InGap etch stop layer **103** may be grown on top of the GaAs channel layer for recess etch reproducibility. As known by skilled people in the field, other layered structures may be fabricated for other types of MESFET and are intended to be encompassed by this invention.

In other embodiments, the epitaxial layers **122** form the epitaxial structure for a pHEMT. The set of epitaxial layers **122** may further comprise a lower GaAs barrier layer, an InGaAs channel layer and an AlGaAs Schottky barrier layer. Double delta doping may be used between these layers to further improve the performance. A thin (about 20 nm) highly doped InGap etch stop layer may be grown on top of the AlGaAs Schottky layer for recess etch reproducibility. Depending on the application, the pHEMT epitaxial structure may be formed by different layer structure and doping methods known to skilled people in the field.

After completion of the growth of the first epitaxial structure **102**, a second epitaxial structure is then grown on top of the first epitaxial structure **102**. In **Fig. 1**, the second epitaxial layer further comprises a highly doped GaAs contact layer **104** that is grown on top of the etch-stop layer **103**. The contact layer **104** may be shared by the FET and the HBT. The contact layer **104** serves as the cap layer for the FET and the subcollector layer for the HBT. The requirements for the contact layer may include low resistivity for both the FET and the HBT. The doping concentration in this layer can be the maximum doping concentration achievable from the growth technology. In an illustrative example, an n-type Silicon doping with a doping concentration of greater than $4.0 \times 10^{18} \text{ cm}^{-3}$ is used for the contact layer **104**.

The thickness of the contact layer **104** depends on the application. The thickness of the contact layer may be chosen based on the following trade-off. The thickness of the subcollector layer may be increased so that the HBT does not have excessive collector resistance and degraded performance. On the other hand, a thinner cap may be preferred to minimize surface topology and simplify the FET fabrication process. More specifically, in the embodiment shown in **Fig. 1**, the thickness of the contact layer **104** is selected based on a sensitivity study of the relationships between HBT characteristics and subcollector thickness. Such a study may be performed using, for example, a physical device simulator, such as the ATLAS device simulation software provided by SILVACO International, headquartered in Santa Clara, CA. **Figs. 2a-2b** illustrate the results of a sensitivity study of the relationships between subcollector thickness and the power-added efficiency (PAE), cut-off frequency (f_t) and maximum oscillating frequency (f_{max}) characteristics of the HBT. Specifically, curve **220** in **Fig. 2a** shows the relationship between subcollector thickness and the power-added efficiency (PAE). Curve **230** of **Fig. 2b** shows the relationship between subcollector thickness and the cut-off frequency (f_t). Curve **240** of **Fig. 2b** shows the relationship between subcollector thickness and the maximum oscillating frequency (f_{max}). A thickness of 350 nm may be selected for the contact layer **104**, based in part on the result of this study.

The rest of the HBT layers may be fabricated on top of the contact layer **104** using existing HBT fabrication Technologies. In the embodiment shown in **Fig. 1**, for example, an n-type GaAs collector layer **105** of thickness from about 800 nm to about 1200 nm is grown on top of the contact layer **104**. A p-type GaAs base layer **106** and an n-type InGaP emitter **107** layer are then grown on the collector layer **105** followed by a highly doped InGaAs contact layer **108**. The HBT structure described above is a generic form. The thickness and doping characteristics of the HBT structure may be optimized further for specific applications. For example, the collector layer **105** may comprise two lightly doped GaAs layers. The base layer **106** may be about 110 nm thick and doped with carbon at a concentration of about $4.0 \times 10^{19} \text{ cm}^{-3}$. The emitter layer **107** may be about 50 nm thick and doped with silicon with a doping concentration of about $3.0 \times 10^{17} \text{ cm}^{-3}$. The contact layer **108** may be about 40 nm thick and doped with Tellurium (Te) with a doping concentration of $1.0 \times 10^{19} \text{ cm}^{-3}$. A thin (about 20 nm) InGaP etch

stop layer **124** may be grown between the contact layer **104** and the collector layer **105**. The epitaxial layers **102-108** described above can be fabricated in a single MOCVD or MBE growth run. **Fig. 3** summarizes the characteristics of each layer in the epitaxial structure in the embodiment shown in **Fig. 1**.

The fabricated epitaxial structure may then be processed to fabricate the integrated HBT and FET pair. **Fig. 4** shows the process flow used in the fabrication of HBT/FETs according to one embodiment of this invention. **Fig. 5** illustrates a cross-section view of the integrated pair of HBT and FET formed during the process shown in **Fig. 4**. Epitaxial layers **102-108** are first grown on a wafer substrate **101** in step **400**. In step **410**, the emitter contact **110** is deposited on the wafer after establishing alignment keys on the wafer. In this step, the emitter area **111** is first defined using photoresist. Next, the emitter metal film **112** is deposited over the photoresist. The emitter film **112** may be formed by metals such as Ti, Pt, Pl, Au, Al, or Cu or metal compounds or alloys formed using these metals. The emitter film **112** may be deposited using well-known physical-vapor deposition (PVD) methods such as e-beam evaporation, plasma spray deposition, or sputtering. In the embodiment shown in **Fig. 4**, a Ti/Pt/Au or Pt/Ti/Pt/Au emitter film **112** is deposited on the photoresist by e-beam evaporation. Those portions of emitter film on the photoresist but not on the emitter area are then removed using the well-known liftoff technique.

In step **420**, the emitter of the HBT is formed by etching the emitter layer **107** and the contact layer **108**. In the embodiment shown in **Fig. 4**, the emitter layer **107** and the contact layer **108** are placed in a phosphoric acid-based chemistry that is selective to InGaP to etch the emitter after depositing the emitter contact.

In step **430**, the base of the HBT is formed. In this step, the base area **114** is first defined using photoresist. Base contact **115** is then deposited on the photoresist using similar PVD and liftoff technologies as described above. In **Fig. 4**, an InGaP etch through the photoresist openings may be performed prior to base metal evaporation to define the InGaP ledge and expose the base layer **106** for base contact deposition. The InGaP layer **107** may be etched in a hydrochloric acid based chemistry which is selective to GaAs. After depositing the base contact

115, the base layer **106** is then etched to produce the base of the HBT. In the embodiment shown in **Fig. 4**, the base layer **106** is etched in a phosphoric acid-based chemistry that is selective to GaAs.

In step **440**, the collector of the FET is formed. In this step, the collector area **117** is first formed using photoresist. Collect contacts **118** are then deposited on the photoresist using similar PVD and liftoff technologies as described above. In **Fig. 4**, the collector layer **105** is first etched in a phosphoric acid based chemistry for the GaAs layer **105** and then etched in a hydrochloric acid based chemistry for the InGaP layer **124**.

In step **450**, an isolation barrier **130** is implanted after the collector etch to isolate the HBT and the FET so that the HBT and the FET can be optimized independently. The subcollector layer is exposed except underneath the HBT base area. A passivation layer may be deposited on the wafer using well-known chemical vapor deposition (CVD) methods to protect the HBT device during subsequent process steps. A nitride passivation layer is deposited on the wafer using plasma-enhanced CVD (PECVD). Besides isolating the HBT and the FET, the isolation barrier **130** may also be used to isolate the HBT/FET pair from other devices such as diodes or resistors that are fabricated on the same substrate. The isolation barrier **130** may be implanted using well-known ion or trench implantation techniques. In **Fig. 4**, the isolation barrier **130** may be formed using a He^+ ion implantation, wherein the isolation pattern is defined using a thick photoresist mask.

In step **460**, the source contact **132** and the drain contact **134** of the FET are deposited on the wafer using well-known metal evaporation and liftoff technologies. The contacts **132** and **134** are made from AuGeNi and these contacts are deposited by evaporation of AuGeNi and the corresponding liftoff technique. In an alternative embodiment, the Collector contacts **118** are deposited in this step instead of in step **440**.

In step **470**, channel recess etch for the FET is performed. In this step, the FET recesses area **136** is first defined and the cap layer **104** is then etched. The cap layer **104** is etched in a phosphoric acid based chemistry for GaAs and the InGaP layer **103** is then etched in a

Hydrochloric acid based chemistry for InGaP. The InGaP etch stop layer **103** ensures a uniform and reproducible etch.

In step **480**, the FET gate **138** is formed. The FET gate formation process may depend on the specific device structure and application requirements. For example, for driver or amplifier applications, a low resistance gate may be required and for such applications a T-gate process block may be introduced at this step. For applications such as dc/rf switch, an evaporated gate may be sufficient. The fabrication of T-gates and evaporated gates are well-known in the art. In the embodiment shown in **Fig. 4**, an evaporation gate is fabricated as follows. First, the FET gate is defined by a photoresist mask. The photoresist mask may be optimized for thickness to provide adequate coverage over the topology and for the minimum required gate length. Next, gate metal of TiPtAu is deposited by e-beam evaporation and lift-off technique. After completion of the FET gate **138**, a nitride film may be deposited to passivate the FET.

The integrated HBT/FET pair fabricated may be further processed for passive component and interconnect fabrication. These steps can be performed using conventional IC fabrication techniques.

Devices fabricated using the integrated HBT/FET Technology described above show performance equivalent to similar non-integrated “stand-alone” HBT or FET transistors. This makes it possible to use them in commercial applications with no penalty in performance but with significant improvement in integration opportunities. The characteristics of the HBT and FET fabricated based on the epitaxial structure shown in **Fig. 3** are summarized in **Fig. 6** and **Fig. 7**. Since bipolar and field effect transistors are de-coupled by the isolation **130**, the epitaxial layers that form these devices can be optimized independently to achieve any given device characteristics.

The method of integrating bipolar and field effect transistors described in this invention is not limited to GaAs-based devices alone. It can be used equally effectively on any set of bipolar and field effect transistors that can be fabricated using epitaxial active layers on the same substrate. Examples of bipolar and field effect transistor pairs may include, but not limited to, InP-based HBT and InP FET/pHEMT,

GaN based HBT and GaN pHEMT/FET. Moreover, the integrated HBT and FET devices may be fabricated with alternative process flows, etch chemistries and ohmic contact metalizations. As an illustrative example, citric acid and sulfuric acid based chemistries may be used to selectively etch or dry etch GaAs/AlGaAs layers on InGaP layers. In another illustrative example, the FET recess and gate layers may be formed right after the formation of the HBT base.

The field effect transistor can be optimized for particular applications and can be either enhancement mode (E-mode) or depletion mode (D-mode) or it can be designed to provide both E and D mode FETs. E/D FETs are especially desirable for the implementation of digital logic functions. The Field Effect Transistor can be realized with alternative epitaxial layer structures known in the industry. Examples of alternative epitaxial layers include but not limited to pHEMT with InGaP as the Schottky layer, pHEMT with AlAs etch stop layer, double recessed pHEMT and MESFET, HIGFET and Hi/Lo MESFET.

Based on the above description, it may occur to any person skilled in the art that passive components such as N-resistor, NiCr resistor, MIM capacitor, spiral inductors, backside via and global and local interconnects may also be fabricated using processes similar to the processes described above.

While the above invention has been described with reference to certain preferred embodiments, the scope of the present invention is not limited to these embodiments. One skilled in the art may find variations of these embodiments which, nevertheless, fall within the spirit of the present invention, whose scope is defined by the claims set forth below.